

Correlation of Nucleate Boiling Data for Downward Facing Surfaces With and Without Coatings

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ABSTRACT

Downward-facing boiling data gathered in the Subscale Boundary Layer Boiling (SBLB) facility were analyzed in this study. The objective is to investigate the efficacy of using vessel coating for the enhancement of boiling heat transfer on surfaces having the same geometry as a typical nuclear reactor vessel. Two types of boiling data were studied, one for the case with coatings and the other without coatings. Correlation equations were obtained for both types of data using the least-square technique. It was found that vessel coating could significantly enhance boiling heat transfer and as such, it can be used for effective cooling of the reactor vessel under severe accident conditions.

INTRODUCTION

In-vessel coolability of core melt is an important issue in addressing a postulated inadequate core-cooling event in nuclear reactors. In such an event, a significant amount of core material can become molten and relocate downward into the lower head of the reactor vessel as happened in the Three Mile Island Unit 2 accident.¹ To assure long-term retention and cooling of the core melt within the reactor vessel, new safety measures have been implemented. Passive cooling consists of flooding the reactor cavity and removing enough decay heat to cool the molten material in the lower head of the reactor. Thus, thermal failure of the reactor vessel can be prevented and the core melt will remain in-vessel.

In this study, downward-facing boiling data gathered in the Subscale Boundary Layer Boiling (SBLB) facility were analyzed. The analysis serves to investigate the efficacy of using vessel coating for enhancement of boiling heat transfer on surfaces of the same geometry as a typical nuclear reactor vessel.

LITERATURE REVIEW

Boiling Phenomena Observed on an Upward Facing Surface

Heat transfer associated with the change of phase from the liquid to the vapor state is called boiling and it is sustained as heat continuously transfers from a solid surface, this allows for large heat transfer rates as temperature varies on a small scale. The boiling process characterizes itself by the formation of vapor bubbles, which grow and subsequently detach from the surface.² This process can be calculated using the Newton's law of cooling for which the heat transfer coefficient changes as the dynamics of the bubble formation affects the surface's liquid motion. The process can also be examined with the boiling curve, which displays the heat flux against the change in the excess temperature. The boiling regimes include free convection, nucleate, transition and film each of these is a function of the excess temperature.

The boiling curve is a function of pressure and is unique for each pure substance. For water at one atmosphere, free convection boiling exists when the excess temperature is less than or equal to 5°C. The *onset of nucleate boiling*, ONB, is the boundary point between the free convection and nucleate regimes; it is at temperatures below this point that bubble inception would not occur and free convection effects determine the fluid motion. The convection coefficient depends on whether the flow is laminar or turbulent and it varies as the excess temperature is raised to the one fourth or one third power.

Nucleate boiling exists in the range of temperature between the ONB and the point where *critical heat flux* is reached which is approximately 30°C. In this range there exists both the *isolated bubbles* and *jets and columns* regimes. In the former regime, most of the heat exchange is through direct transfer from the surface to liquid in motion and not through the vapor bubbles rising from the surface.² The latter regime is characterized by having the vapor escape as jets that merge into parts of the vapor, it is at this point that increasing excess temperature activates more nucleation sites and the increment of bubble formation causes bubble interference and coalescence. In this regime, there exists a point at which the convection coefficient changes from being at its maximum to decreasing as the excess temperature increases, this increase in temperature exceeds the reduction in the convection coefficient which allows for the heat flux to continue increasing.

Transition boiling also termed unstable film boiling or partial film boiling occurs between the *Critical heat flux* point and the *Leidenfrost* point, which is the point where the heat flux is minimum. In this region, a vapor film begins to form on the surface but it still varies to nucleate boiling. Since the conductivity of the vapor is less than the thermal conductivity of the liquid, the convection coefficient decreases as the excess temperature increases therefore decreasing the heat flux.

Film boiling begins at the *Leidenfrost point* where the surface is already covered by a vapor blanket. In this regime heat transfer takes place by conduction and radiation through the vapor. Heat flux increases as the excess temperature is increased thus making radiation through the vapor film more significant.

In order to analyze nucleate pool boiling, it is necessary to predict the number of surface nucleation sites as well as the rate at which at each site bubbles are originated. The first and most widely used correlation for nucleate boiling was developed by Rohsenow³ which applies only for clean surfaces but is very useful to estimate the excess temperature from the knowledge of surface heat flux. While it is desirable to operate near the critical heat flux point it is still

necessary to keep in mind the dangers of dissipating heat beyond this point. An expression that approximates the heat flux under these conditions was obtained by *Kutateladze* and *Zuber*, which is independent of surface material and is weakly dependent upon the heated surface geometry.² Regardless of the geometry, critical heat flux strongly depends on pressure and it has been demonstrated experimentally that the peak flux increases with the increment of pressure up to one third of the critical pressure, which then falls to zero at the critical pressure level.

In film pool boiling, a continuous vapor film blankets the surface at temperatures beyond the Leidenfrost point and there is no contact between the liquid phase and the surface. The condensation theory plays a big role on establishing a correlation because the base film boiling correlations are based on the theory due to the fact that the stable film of vapor allows a resemblance to the conditions of laminar film condensation, however this does not hold true for small surfaces. It is not until the surface temperature reaches over 300°C that radiation heat transfer across the vapor film becomes significant.²

Some of the parametric effects on pool boiling include the gravitational field, liquid subcooling and solid surface conditions. Overall pool boiling has low gravity effects and the correlations confirm the dependence on $g^{1/4}$, although for nucleate boiling, heat flux is nearly independent of gravity. Near the onset of nucleate boiling, evidence shows that gravity can influence bubbled-induced convection. Subcooling means that the liquid in the system is maintained at a temperature below the saturation temperature; in the natural convection regime the summation of the excess and the subcooled temperatures is raised to the five-fifths power and in nucleate boiling this is negligible while in film boiling the heat flux is increased strongly with the increment of the subcooled temperature. Surface roughness has a negligible effect on minimum and maximum heat fluxes, but increasing the surface roughness can increase the heat flux largely in the nucleate boiling regime because the surface provides vapor traps that increase the sites for bubble growth. However after prolonged boiling the effects diminish.

Boiling on a Downward Facing Surface

Cheung et al⁷ developed a subscale boundary-layer boiling (SBLB) test facility to investigate the critical heat flux (CHF) and the pool-boiling phenomena on the outer surface of a simulated reactor pressure vessel (RPV) lower head. The SBLB was developed using a scaling analysis consisting of a high-heat-flux level hemispheric vessel fully submerged in a pressurized water tank with a condenser unit. All the important characteristic time ratios were preserved in the facility so the entire process was simulated properly and therefore the same effects will occur as in a full-scale reactor.

The experiment was done under both saturated and subcooled conditions a two-phase liquid-vapor boundary-layer flow was found to develop on the vessel outer surfaces as a result of the boiling process.⁴ Saturated boiling formed bubbles in the bottom region of the vessel that were elongated and resembled a pancake shape with a 10 to 60-mm diameter; the bubbles in the upper portion were similar to spheres but having a much smaller size. At departure, the elongated vapor bubbles from the bottom region flowed upward along the heating surface carrying away the growing bubbles in the downstream locations. Therefore the nucleate boiling process depended strongly on the upstream flow conditions in the two-phase boundary layer. Subcooled boiling decreased the size of bubbles and increased the bubble growth and departure. The vapor

bubbles located at the bottom center region shrank quickly after departure, and the size of them depended on the level of subcooling.

High-heat-flux levels produced a cyclic vapor ejection process in the bottom region of the vessel; the elongated vapor bubbles were squeezed up against the wall by the local buoyancy force and then grew rapidly on the heating surface. The individual nucleation sites were feeding the envelope of each large vapor mass, as the large mass grew to a critical size, it was ejected violently upward in all directions. This ejected vapor mass formed a ring as it traveled radially upward with a new vapor mass starting to grow inside the ring.⁴ The vapor mass continued to break off into several large vapor slugs due to the diverging area of the vessel. These slugs carried away local vapor bubbles but tended to bypass the large vapor slugs growing on the heating surface in the downstream locations.

As the heat-flux level was closer to the local CHF limit, the cyclic ejection of the vapor masses became explosive and highly chaotic and the characteristic frequency of the ejection cycle tended to increase slowly. At a closer view, a thin liquid film beneath each elongated vapor slug was seen; the micro-layer was growing on the heating surface. The liquid film fed the small vapor masses generated at nucleation sites to the large vapor slug, and it was this film under the large vapor slug that prevented local dry-out of the heating surface. The characteristic frequency near the local CHF limit was approximately 4 Hz for saturated boiling. This implies that the vapor ejection cycle lasted about 0.25 s. For 90% of this time, the vapor slug covered the heating surface. The local boundary-layer thickness as well as the local liquid and vapor velocities increased considerably from the bottom center to the upper edge of the vessel. As a result, the rate of nucleate boiling was highly non-uniform on the outer surface of the vessel; the lower portion data was quite different from those for the upper portion. The maximum nucleate boiling heat flux near the bottom center was only 0.4 MW/m^2 for saturated boiling and in the upper portion the highest was approximately 1.4 MW/m^2 with 10°C subcooling.

Guo and El-Genk⁵ studied pool boiling curves of a flat disk for inclinations of various angles (0° to 90°) by quenching with saturated water at near atmospheric pressure. Although the study was not using hemispherical surfaces, it still helps understand the changes of heat flux, quenching time and vapor film development. The study was done using a copper disk with a 12.8-mm thickness and a 50.8-mm diameter, which was insulated with marinite on the sides and at the back surface and housed in a Bakelite skull. The disk was submerged 57-mm below the water level of a large Pyrex beaker and heated to 533-539 K before quenching.

The time that it took to quench the entire surface however, increased as the inclination decreased. The time needed to quench a downward facing surface having an initial wall superheat of 160 K is six times that for a 5° inclination and 23 times that for a 90° inclination.⁵ At high wall superheats, downward facing surfaces develop a thick wavy but stable vapor film on the disk's surface with vapor escaping from its edges. As the temperature decreases, the vapor film becomes more stable and the vapor escape frequency decreases. At minimum film boiling, the vapor film acts like a mirror and vapor no longer escapes, eventually the film collapses as the wall superheat becomes very low.

The study also presented that the critical heat flux and minimal film boiling heat flux increased with increasing angle of inclination. However for downward facing surfaces, both heat fluxes are significantly lower than those for inclination angles.

Data Reduction Techniques

The presentation of data as a set of discrete points using a smooth continuous function is a problem of often interest in engineering. Curve fitting is based upon a function $f(x)$, x is the independent variable and $f(x)$ is a dependent variable such as a material property, a heat flux, etc. The two basic approaches to curve fitting are an exact fit and a best fit. The first approach is appropriate for data with high-level accuracy such as material property data. The second approach is more useful for a large number of data points because it approximates the curve and minimizes the given data.

Interpolation is used to determine the dependent variable $f(x)$ at any value in the data points and extrapolation is used to determine $f(x)$ outside the given data range. Both are used to fit an exact curve to a finite number of discrete points to then apply a mathematical operation to the smooth curved. Exact fits in engineering are mainly composed of an approximating polynomial, which passes through each data point and yields an exact value. A polynomial of degree n is used to describe linear, quadratic, or cubic equations and so on. Larger points require higher order of polynomials and the coefficients vary in size depending on the independent variable. Lagrange interpolation is another method for exact fitting; it uses a special form of interpolating polynomial called the Lagrange polynomial. It is applicable to an arbitrary distribution of the x variable, and it does not require the system of equations in order to solve it.

Another form of the polynomial for interpolation is Newton's divided-difference polynomial, which is used for any arbitrary distribution of data points. It resembles a Taylor series expansion because the terms of the equation represent higher-order derivatives that are successively added to increase accuracy. When dealing with spaced data, Newton's interpolating polynomial can be rewritten as the *Newton-Gregory forward interpolation formula* or the *Newton-Gregory backward interpolation formula* using this formula to plug in the data of a forward difference table will yield the interpolating polynomial. The choice of which formula to use comes from the value of x in relation to the given data points, whether it is closer to x_0 or x_n .

The procedures for extrapolation are very similar to interpolation; the same approaches listed above can be used depending on the data but the element of uncertainty must be considered when looking at the final polynomial since extrapolation is based on estimating.

Interpolating polynomials used to yield piecewise exact fit to the data are called spline functions. The method consists on using a thin, flexible strip to draw a smooth curve through the data distribution. On higher order polynomials the methods mentioned previously yield equations of higher degrees that oscillate and/or are wiggly which leads to ill-conditioning and computational difficulties. Therefore it is more common to use the spline functions to get a better approximation over significantly wide data ranges.

Certain data for various applications often contains a significant amount of associated error, for such instances, it is not recommended to use a spline function but rather use an interpolation method that provides a best fit to the given data by minimizing the difference between the given values of the dependent variable and those obtained from the approximating curve.⁶ Linear regression yields a straight line that provides a best fit to a given data set. For data that is poorly represented by straight lines, the method of m th-order polynomial is used, but it is generally restricted to small values of the order m to avoid extensive calculations to determine the coefficients. Least squares is not restricted to polynomials for curve fitting, it can also be applied to other forms with constant coefficients. This includes linearization, which is the process to curve fit nonlinear data by suitable transformations to apply linear regression.

In engineering applications it is often found that some functions depend on more than one variable. Curve fitting is carried out with only one independent variable, taking the other variable at specified values and thus generating a number of curves that fit the data. This process is more convenient than seeking a single function that represents the entire dependence on various independent variables. For such cases, exact fitting and best fitting may be used. A best fit is often more appropriate than an exact fit because of the amount of error that may be involved in the experimental data.

DATA ANALYSIS AND CORRELATION

Review of Experimental Method for the SBLB Data

The system was composed of a water tank, a condenser, segmented and continuous downward facing hemispherical vessels for steady state and quenching experiments, data acquisition software and a photographic system.

Water Tank and Condenser

A cylindrical tank equipped with a reflux condenser was manufactured to conduct all experiments at a gauge pressure of up to 138 KPa. The tank had a diameter of 1.22 m and a height of 1.14 m, the wall thickness was 6.35 mm and for the bottom and top tank covers the thickness was 12.7 mm. The tanks were made of carbon steel because it was strong to sustain the high pressure and the cost was reasonable for the budget, also this is the same material used for most commercial-sized reactor vessels. To protect the tank from corrosion, the interior surface was fully polished and then coated with high-temperature corrosion- and moisture-resistant durable paints. Two large windows were placed on opposite sides of the tank to allow observing of the whole surface and for additional lighting. Both windows were made with acrylic plexiglass of 25.4 mm and 12.7 mm thickness.

The guidance mechanism allowed the tube connected to the test vessel to slide vertically. It was sealed tight with o-rings squeezed against the tube by tightening the outer nut of each ring. The heating of the water was done with three immersion heaters that had a total power of 36 KW, each heater had its own power line connected to individual power supplies of 240 V and maximum capacity of 50 A. three thermocouples were placed at various locations, at the water surface, at the bottom of the tank and in the middle of the tank.

The condenser was made of cylindrical pipe with a diameter of 0.355 m. The opening for the water vapor was of 76 mm in diameter and the housing for the entire condenser was tilted downward to direct the flow towards the 25 mm pipe and avoid disturbance from the condensate on the water surface (See Figure 1). The helical coil inside the condenser was made out of soft copper tubing with an outer diameter of 12.7 mm and a thickness of 1.588 mm. The water flow rate was estimated to be 0.18×10^{-3} kg/s and the length was calculated to be 10 m.

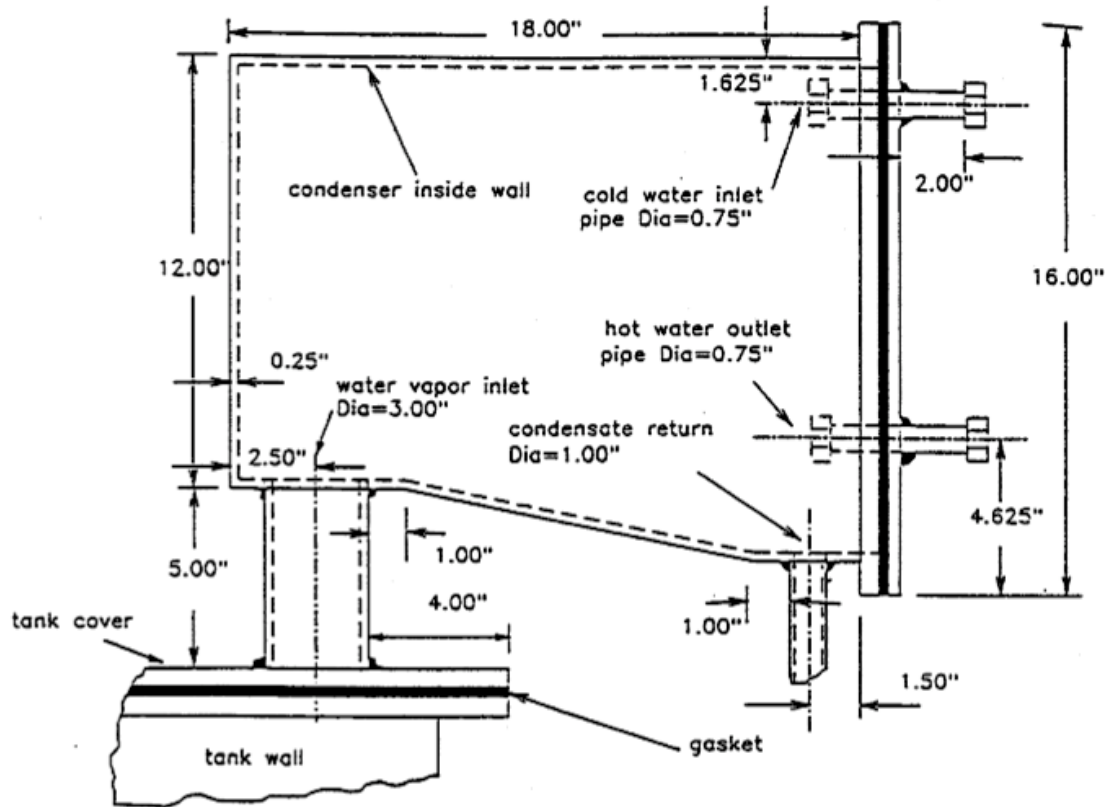


Figure 1. Schematic of the Condenser Housing

Segmented Hemisphere

The segmented hemisphere was composed of five segments all with a wall thickness of 12.7 mm made of stainless steel. An insulating layer made of high temperature silicon rubber material was used to minimize heat transfer between the segments and prevent any leaks (See Figure 2). The cover of the vessel was connected to a flange that was welded to the top segment and was fastened with four screws. To make this connection leak tight, an o-ring was placed between the cover and the flange. The segmented hemisphere had 25 thermocouples of 1.016 mm in diameter but with different depths. These steady-state temperatures recorded by the thermocouples were used to determine the local boiling coefficient on the outside of the surface. The top segment had two thermocouples 180° from each other, segments 2, 3 and 4 had five each and the bottom segment had eight.

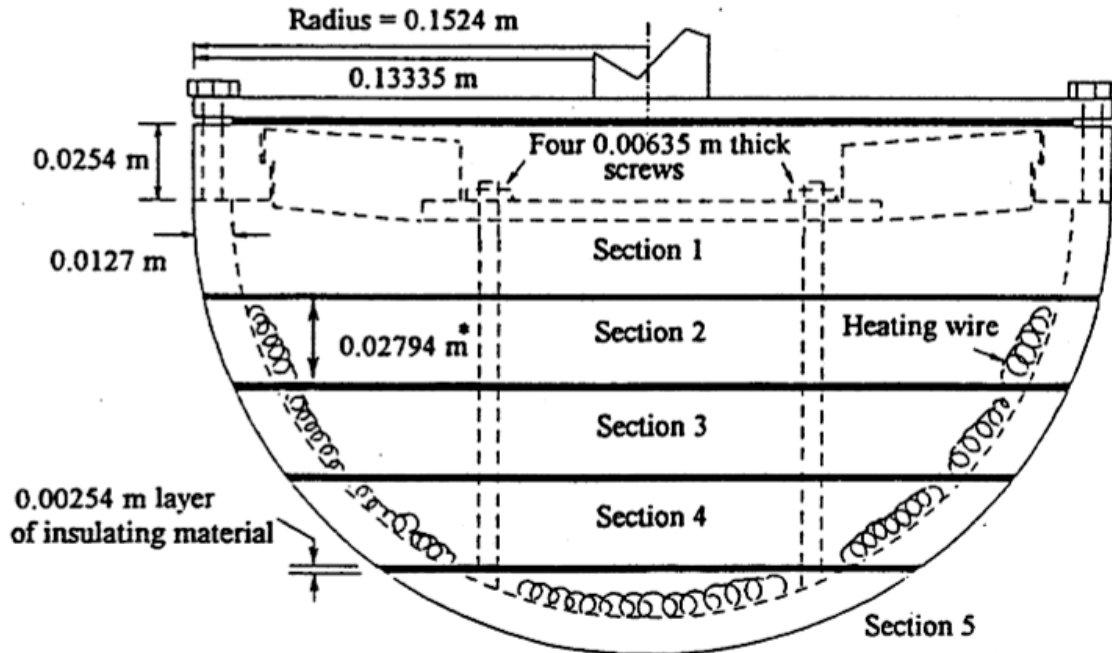


Figure 2. Side View of the Segmented Hemispherical Test Vessel

Continuous Vessels for Steady-State Experiments

The nichrome coil was installed using Plaster Pairs to control the wire spacing on the surface of the vessel by creating a mold first. The circuit began at the bottom center of the mold and then the wire was wrapped around the nails to form the first loop, the process was continued until the wire length was reached. Circuits were done until the surface was covered with the nichrome coil making sure that wires were not touching each other. The wire was then moved to the back of the vessel making sure the shape was untouched a thin layer of high-temperature cement called OB600 from Omega Engineering, Inc. was applied to the surface so the wire did not touch the metal, then it was applied to attach the wire to the surface of the vessel; this was necessary to prevent short circuits.

Continuous Vessels for Quenching Experiments

To investigate the spatial variations of the boiling curve along the outer heating surface, continuous hemispherical vessels made of aluminum and toroidal vessel made of carbon steel was used to conduct the quenching experiments. Thirty gauge K-type were placed along an arc that started at the bottom center and ended close to the upper edge of the vessel. Three other thermocouples were equally spaced on the circumference half way between the bottom center and the equator to check the uniformity of the heating of the hemisphere. Thermocouples were placed in holes of 1.59 mm in depth and diameter and using an aluminum-zinc based solder.

Data Acquisition System

The temperatures at various locations in the vessel were monitored using a personal computer and a data acquisition system. Two Strawberry Tree ACPC-16 boards were installed inside the PC, each containing 16 digital input/output channels and 16 analog input channels. The highest sampling rate possible was dependent on the resolution chosen. In the steady state experiments, high sampling rates were not important, therefore the highest "low noise resolution" was used to help minimize the effect of the interference from the AC power line and the nichrome coil used to heat the vessels. In the quenching experiments, using a high sampling rate was important especially when the time constant of the vessel was low.

A program called DATACOL for transient quenching and steady state experiments was written in compiled BASIC to monitor the thermocouple signals. At the beginning of the program, the resolution, the number of thermocouples to be traced, and the type of sensors used were declared. Then the program performed a calibration of all the analog input channels. The driver of the board used the method of reading all the thermocouple signals multiple times while storing the readings in memory and at the end all the data was put into a single file. During the quenching experiments, it was necessary to heat the vessel before quenching it into the water bath. Therefore, a second program called TEMPDIS was written to monitor the vessel temperature while it was being heated, the program displayed the temperatures at various locations on the screen. It also scanned all the thermocouples once during a specified time period. Then the temperatures collected were displayed on the screen before the thermocouples were scanned again.

Review of Experimental Procedure for the SBLB Data

The tank access-hole cover and the sliding mechanism were removed from the tank assembly to mount the vessel to the vertical sliding mechanism. Then the thermocouple wires and the power supply were inserted inside the stainless steel pipe used to vertically position the vessel. Before mounting the components back to the assembly, the heating surface was polished with #220 emery paper and then cleaned thoroughly with acetone. After putting the vessel together, a hose containing a filter to get rid of unwanted particles was connected to a tap water supply to level the water inside the tank to 0.838 m. When the water level was reached, three immersion heaters were turned on and after four hours the water was heated to saturation temperature. Then the water was heated once again for 15 minutes to degas the water. Lastly the heaters were turned off to cool the water down.

A pump was used to filter the water one more time and to get rid of particles that precipitated during the heating process. Once the filtering process was done, the heaters were turned on again until the desired temperature was reached. This temperature was kept by turning one of the heaters on and off for small amounts of time.

Quenching Procedure

The thermocouples attached to the inside of the vessel were connected to the data acquisition system. The program TEMPDIS was used to monitor the heating of the vessel by displaying the temperatures of every location of all thermocouples. The heating was continued until 350°C were reached, since higher temperatures would lead to melting of the solder that held the thermocouples in place.

After removing the cover underneath the vessel and setting the computer to begin collecting data, the vessel was submerged in the water bath and DATACOL was activated. The stopper on the stainless steel pipe was previously set to let the vessel submerge to 0.304 m.

Steady State Experimental Procedure

After mounting the vessel, the thermocouples and the power supply were connected to the variacs and the data acquisition system. Every variac circuit was equipped with an ammeter to determine the power supplied to each circuit. The vessel was submerged to 0.304-m below the water level. Next, the power to the variacs was turned on to give the desired heat flux at the surface, also the program TEMPDIS was being run to track the temperature variations. These readings were used to determine if the system reached steady state, at this point TEMPDIS was terminated and DATACOL was executed to scan all thermocouples.

Types of SBLB Data to Be Analyzed

Quenching Experiments

The quenching experiments were done using a high-speed video system and a high-speed camera to record and photograph the events. The video recording was viewed in slow motion to take a closer look to the characteristics of the transient two-phase boundary layer.

When a superheated flat plate, disk or surfaces of low curvature facing horizontally upward is suddenly quenched into a saturated liquid, film boiling of the liquid first takes place around the hot object. As the solid temperature drops below the minimum film boiling temperature, transition boiling occurs. On the surface of the object, the activities of vapor film breakdown and release increase progressively in time, and at the peak of these activities, the critical heat flux is reached. Beyond this point, the solid object cools off quickly and approaches the liquid temperature, marking the end of the quenching process. In this study, larger and downward facing surfaces were used which changes the effects of boiling. Changes in the boiling regime from film to transition and then to nucleate did not take place uniformly over the external bottom surface of the hemispherical vessel during the quenching process. Rather, transition from film to nucleate boiling first occurred at the upper edge of the vessel. It then propagated downward along the curved heating surface, and eventually reached the bottom center of the vessel (see Figure 3).⁷

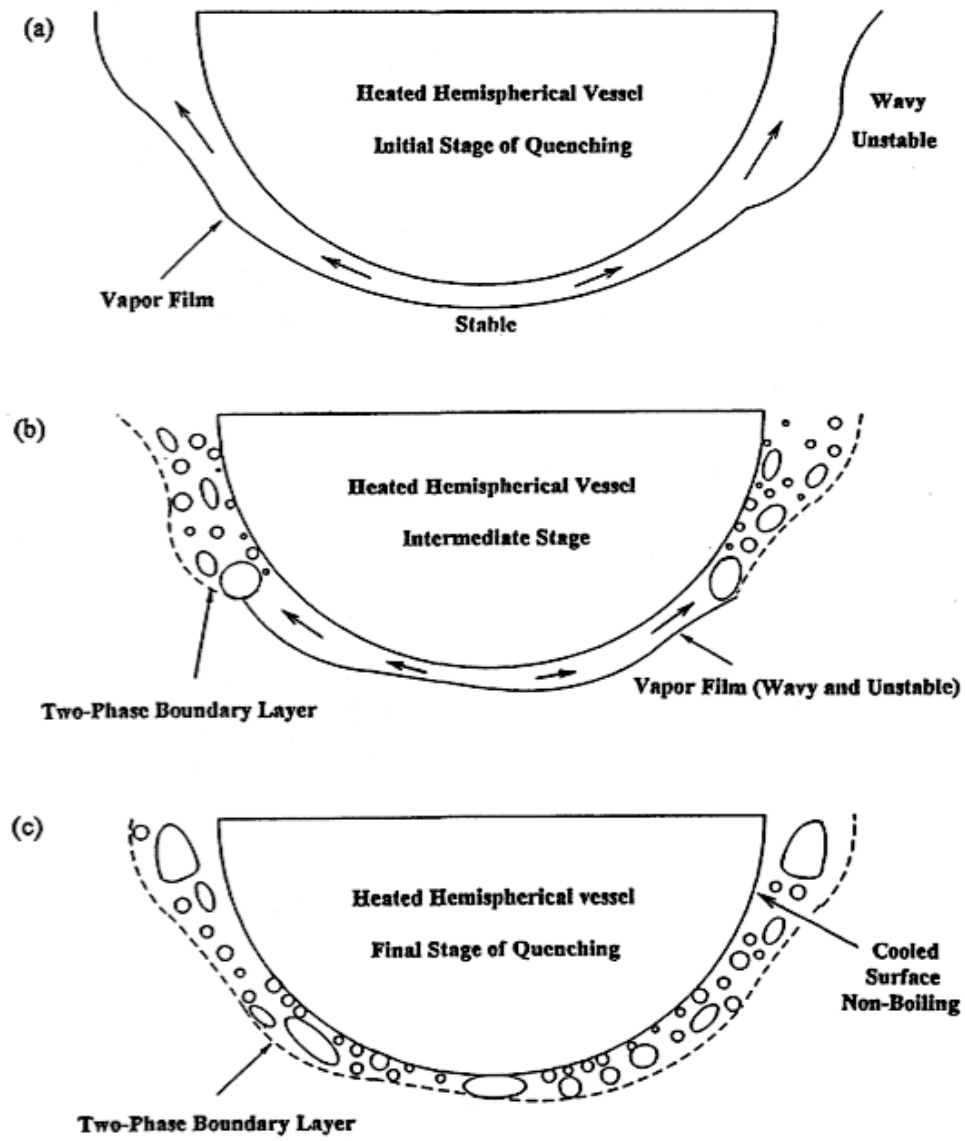


Figure 3. Schematic of the Two-Phase Boundary Layer Configuration in the Three Sequential Stages of Quenching.

Steady State Experiments

For saturated boiling, the vapor bubbles in the bottom center region were much larger than those in the upper portion of the vessel with the entire surface heated at the same power level. The bubbles around the bottom center were elongated and had the shape of a pancake, whereas those in the upper portion were almost spherical. After departure, the large vapor bubbles from the bottom center region gradually transformed into the shape of a spherical cap while washing away the growing bubbles in the downstream location.

RESULTS AND DISCUSSION

Using the least square technique, a correlation equation was found for each set of data to find an appropriate representation of all the readings taken (See Figures 1 and 2).

Noncoated

$$\begin{aligned} \text{Theta} &= 0 \\ q'' &= 0.0056\Delta T_e^{1.3142} \end{aligned}$$

$$\begin{aligned} \text{Theta} &= 18 \\ q'' &= 0.0071\Delta T_e^{1.27} \end{aligned}$$

$$\begin{aligned} \text{Theta} &= 36 \\ q'' &= 0.0044\Delta T_e^{1.4035} \end{aligned}$$

$$\begin{aligned} \text{Theta} &= 56 \\ q'' &= 0.0018\Delta T_e^{1.7283} \end{aligned}$$

Figure 4. Set of Equations for Each of the Measured Angles for the Non-coated Vessel

Coated

$$\text{Theta} = 0$$

$$q'' = 0.0196\Delta T e^{0.8848}$$

$$\text{Theta} = 14$$

$$q'' = 0.0506\Delta T e^{0.6663}$$

$$\text{Theta} = 42$$

$$q'' = 0.0204\Delta T e^{0.9193}$$

$$\text{Theta} = 60$$

$$q'' = 0.1775\Delta T e^{0.4654}$$

Figure 5. Set of Equations for Each of the Measured Angles for the Coated Vessel

The local boiling heat fluxes are plotted against the excess temperature local wall superheat. To get a full spectrum of the non-coated data, every point for all angles is plotted on a log scale vertical axis (See Figure 6). It can be seen that the nucleate boiling rate tended to increase as the change in temperature moves upward from the bottom center toward the equator of the test vessel.

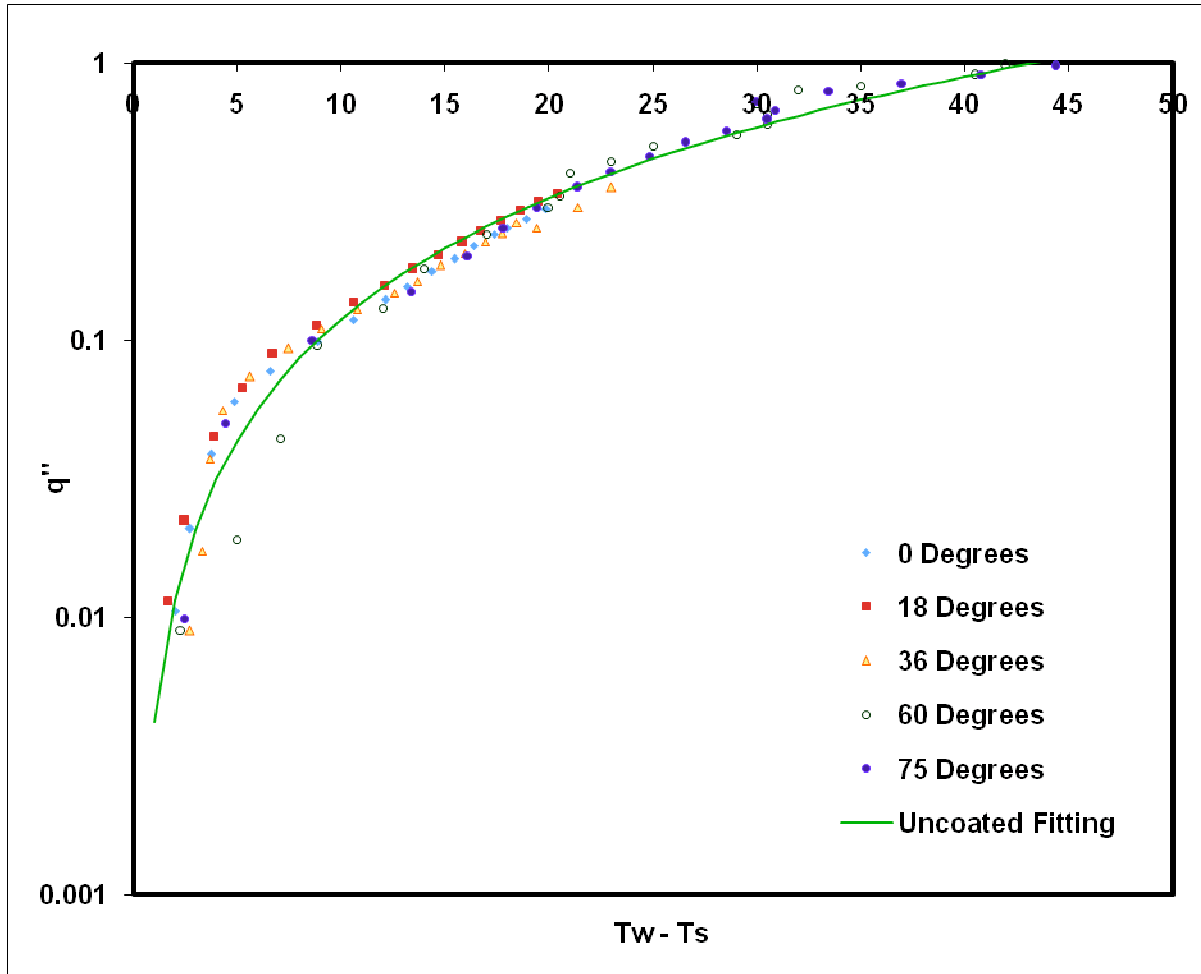


Figure 6. Distribution of the Correlation of Excess Temperature vs. Heat Flux for Non-coated data

Comparing the coated data with the non-coated data displays the enhancement in boiling heat transfer. Depending on the angular position of the vessel, enhancement in boiling heat transfer of up to 100% can be obtained by using surface coatings. At 0 degrees, a small difference is shown (See Figure 7) when comparing the two correlations of data.

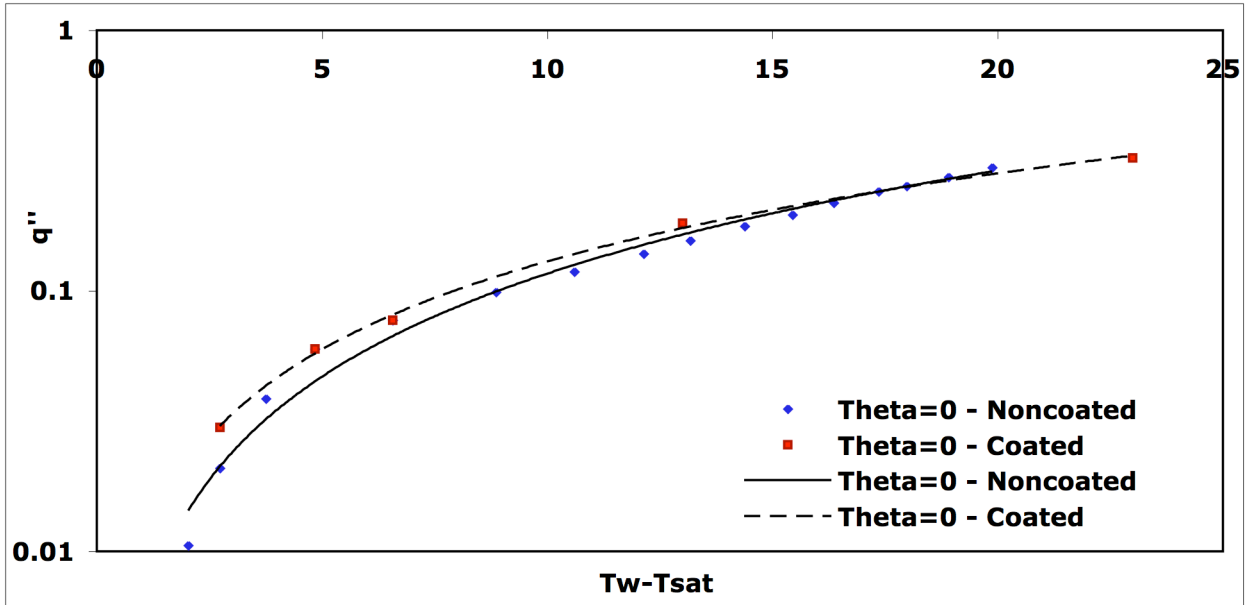


Figure 7. Correlation of Excess Temperature vs. Heat Flux between 0 Degrees Coated and 0 Degrees Non-coated Data

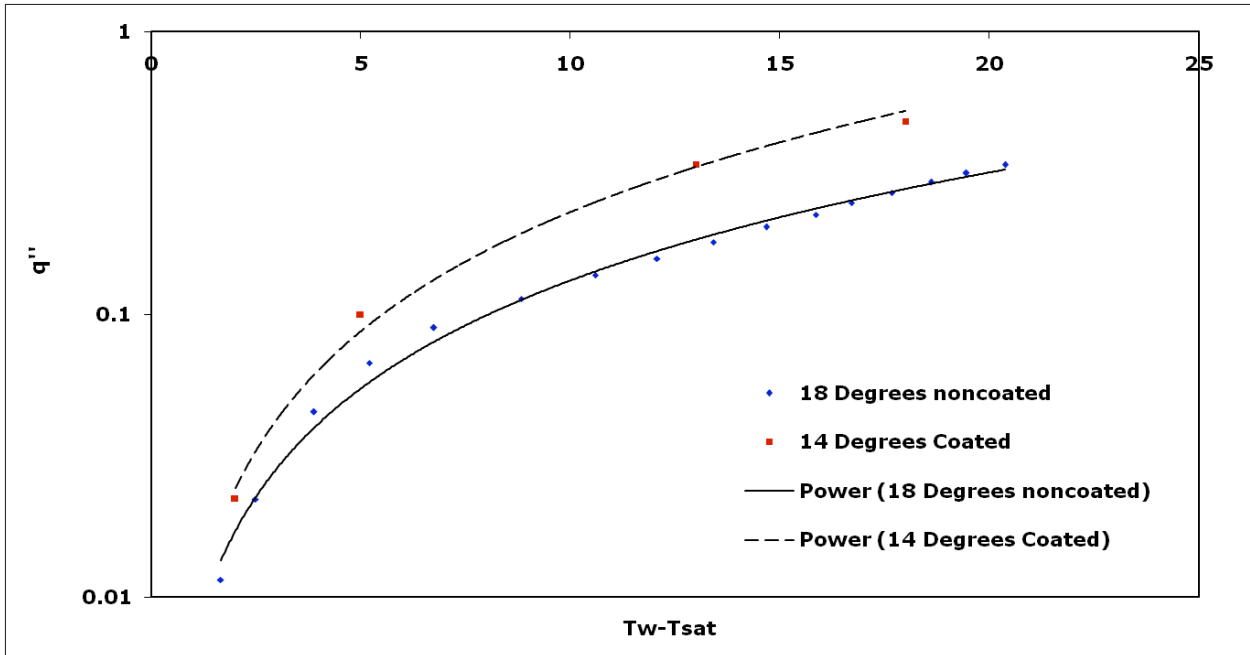


Figure 8. Correlation of Excess Temperature vs. Heat Flux between 14 Degrees Coated and 18 Degrees Non-coated Data

As the angle of inclination increases, the difference between coated and non-coated vessels becomes more evident (See Figures 8 and 9). The biggest difference in the correlation between excess temperature and heat flux can be seen when comparing the bigger angles; a coated vessel at an angle of inclination of 56 degrees has a much higher correlation than a non-coated vessel at 60 degrees (See Figure 10).

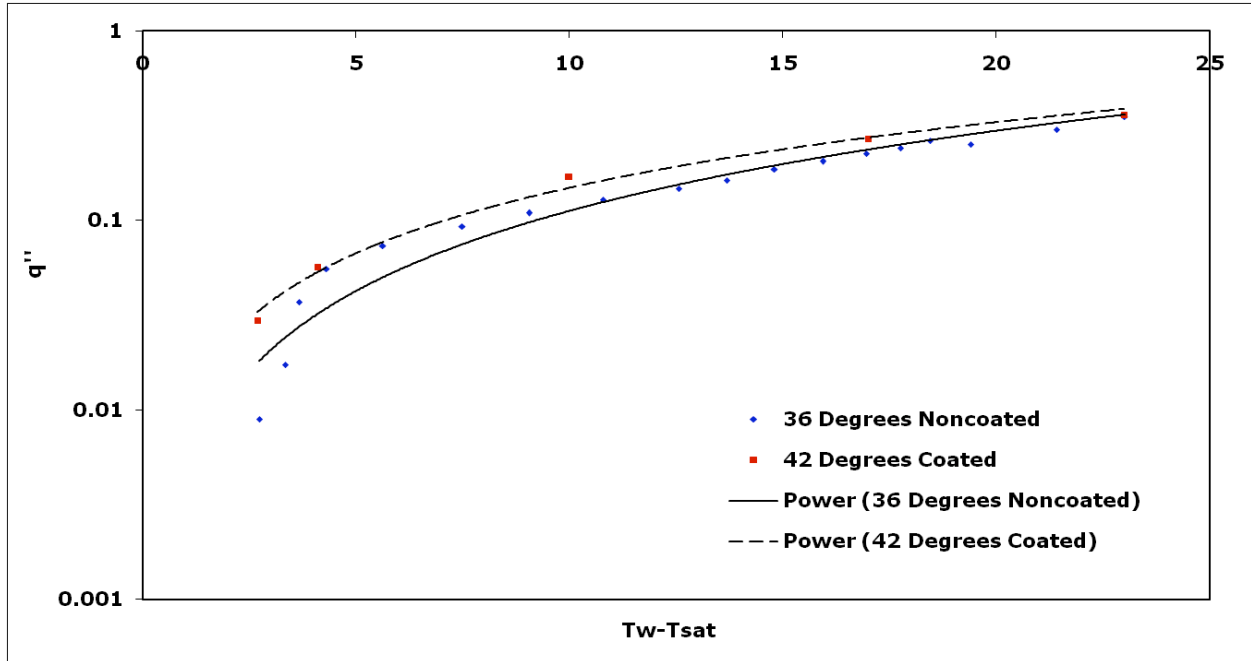


Figure 9. Correlation of Excess Temperature vs. Heat Flux between 42 Degrees coated and 36 Degrees Non-coated Data

Guo and El-Genk⁵ demonstrated that the critical heat flux decreases with decreasing inclination; in this study the same can be seen when comparing all the distributions of the data. The study done by Brundage⁸ demonstrated that the excess temperature relating to the critical heat flux varied from the bottom to the top location, the current data shows that the higher the inclination, the higher the heat flux.

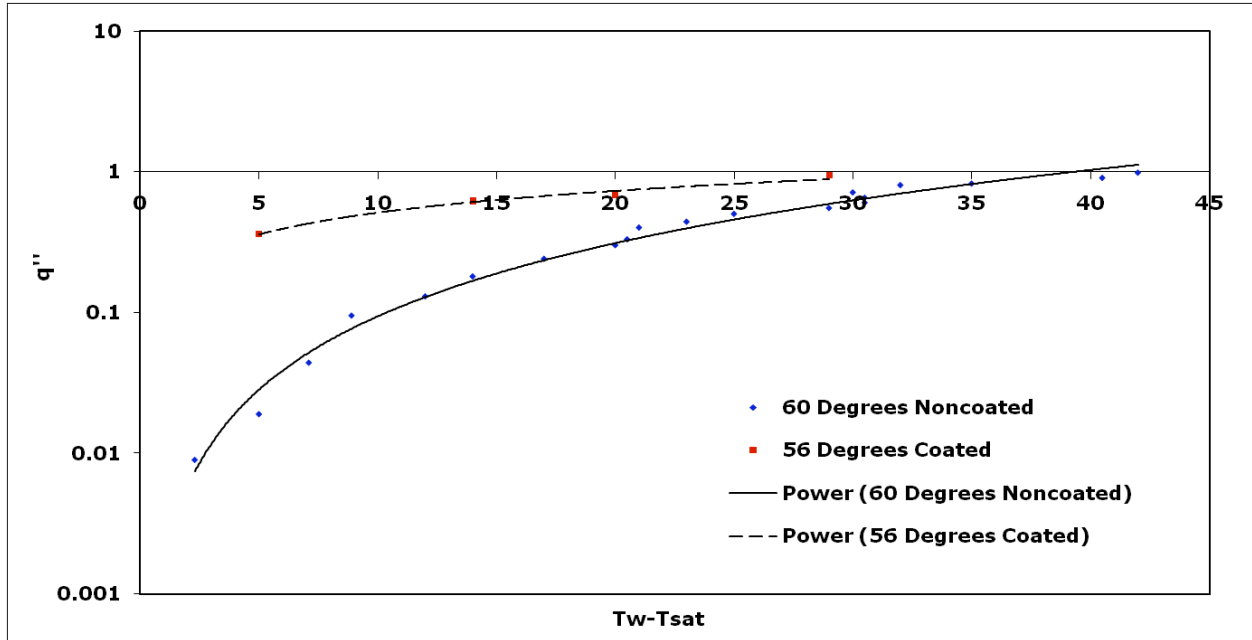


Figure 10. Correlation of Excess Temperature vs. Heat Flux between 56 Degrees Coated and 60 Degrees Non-coated Data

CONCLUSION

Under all cooling conditions, the nucleate boiling heat fluxes observed for the cases with coating were consistently higher than the corresponding cases without coating. Depending on the angular position of the vessel, enhancement in boiling heat transfer of up to 100% can be obtained by using surface coatings. The largest difference in the correlation between the local heat flux and the excess temperature can be seen at higher angular positions. The use of surface coatings is a viable technique for enhancing the cooling of the reactor vessel under accident conditions. The cooling enhancement method under consideration is entirely passive and as such it is not subjected to human error. Should an unlikely event of core-meltdown happen; the reactor vessel could be cooled effectively to prevent melt-through of the reactor vessel by the molten core material.

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